



Study of Time-Dependent CP -Violating Asymmetries in $b \rightarrow s\bar{q}q$ Decays

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Abstract

We present a measurement of CP -violation parameters in the $b \rightarrow s\bar{q}q$ penguin transitions ($q = s, u, d$) based on a 78 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB energy-asymmetric e^+e^- collider. One neutral B meson is reconstructed in the ϕK_S^0 , $K^+K^-K_S^0$, or $\eta'K_S^0$ decay channel, and the flavor of the accompanying B meson is identified from its decay products. CP violation parameters for each of the three modes are obtained from the asymmetries in the distributions of the proper-time intervals between the two B decays.

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In the standard model (SM), CP violation arises in weak interactions from an irreducible complex phase in the Kobayashi-Maskawa (KM) quark-mixing matrix [1]. In particular, the SM predicts CP -violating asymmetries in the time-dependent rates for B^0 and \overline{B}^0 decays to a common CP eigenstate f_{CP} [2]. Recent measurements of the CP -violating parameter $\sin 2\phi_1$ by the Belle [3, 4] and BaBar [5] collaborations established CP violation in neutral B meson decays mediated by the $b \rightarrow c\overline{c}s$ tree transition [6] at a level consistent with KM expectations.

Despite this success, many tests remain before one can conclude that the KM model provides a complete description. For example, the charmless decays $B^0 \rightarrow \phi K_S^0$, $B^0 \rightarrow K^+ K^- K_S^0$, and $B^0 \rightarrow \eta' K_S^0$, which are mediated by the $b \rightarrow s\overline{s}s$ transition ($B^0 \rightarrow \eta' K_S^0$ also receives $b \rightarrow s\overline{d}d$ and $b \rightarrow s\overline{u}u$ penguin contributions) are potentially sensitive to new CP -violating phases from physics beyond the SM [7]. SM contributions from the $b \rightarrow u\overline{u}s$ tree diagram are expected to be highly suppressed [8, 9]. Thus, the SM predicts that CP violation measurements in these charmless modes should yield $\sin 2\phi_1$ to a good approximation. Consequently, a significant deviation in the time-dependent CP asymmetry in these modes from what is observed in $b \rightarrow c\overline{c}s$ decays would be evidence of a CP -violating phase not expected in the KM model.

In the decay chain $\Upsilon(4S) \rightarrow B^0 \overline{B}^0 \rightarrow f_{CP} f_{\text{tag}}$, where one of the B mesons decays at time t_{CP} to a final state f_{CP} and the other decays at time t_{tag} to a final state f_{tag} that distinguishes between B^0 and \overline{B}^0 , the decay rate has a time dependence given by [10]

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q \cdot [\mathcal{S} \sin(\Delta m_d \Delta t) + \mathcal{A} \cos(\Delta m_d \Delta t)] \right\}, \quad (1)$$

where τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, $\Delta t = t_{CP} - t_{\text{tag}}$, and the b -flavor charge $q = +1$ (-1) when the tagging B meson is a B^0 (\overline{B}^0). The CP -violating parameters \mathcal{S} and \mathcal{A} are given by

$$\mathcal{S} \equiv \frac{2\text{Im}(\lambda)}{|\lambda|^2 + 1}, \quad \mathcal{A} \equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}, \quad (2)$$

where λ is a complex parameter that depends on both the $B^0 \overline{B}^0$ mixing and on the amplitudes for B^0 and \overline{B}^0 decay to f_{CP} . To a good approximation in the SM, $|\lambda|$ is equal to the absolute value of the ratio of the $\overline{B}^0 \rightarrow f_{CP}$ to $B^0 \rightarrow f_{CP}$ decay amplitudes. The SM predicts $\mathcal{S} = -\xi_f \sin 2\phi_1$, where $\xi_f = +1(-1)$ corresponds to CP -even (-odd) final states; and $\mathcal{A} = 0$ (or equivalently $|\lambda| = 1$) for both $b \rightarrow c\overline{c}s$ and $b \rightarrow s\overline{s}s$ transitions.

In this paper, we report the first measurement of CP asymmetries in $B^0 \rightarrow \phi K_S^0$ and $K^+ K^- K_S^0$ decays, and an improved measurement for $B^0 \rightarrow \eta' K_S^0$ decay [11] based on a 78 fb^{-1} data sample, which contains 85 million $B\overline{B}$ pairs. Data are collected with the Belle detector at the KEKB energy-asymmetric e^+e^- (3.5 on 8 GeV) collider [12] operating at the $\Upsilon(4S)$ resonance. At KEKB, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beamline (z). Since the B^0 and \overline{B}^0 mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (cms), Δt can be determined from the displacement in z between the f_{CP} and f_{tag} decay vertices: $\Delta t \simeq (z_{CP} - z_{\text{tag}})/\beta\gamma c \equiv \Delta z/\beta\gamma c$.

The Belle detector [13] is a large-solid-angle spectrometer that includes a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM).

We reconstruct B^0 decays to ϕK_S^0 and $\eta' K_S^0$ final states for $\xi_f = -1$, and $B^0 \rightarrow K^+ K^- K_S^0$ decays that are a mixture of $\xi_f = +1$ and -1 . $K^+ K^-$ pairs that are consistent with $\phi \rightarrow K^+ K^-$ decay are excluded from the $B^0 \rightarrow K^+ K^- K_S^0$ sample. We find that the $K^+ K^- K_S^0$ state is primarily $\xi_f = +1$; the $\xi_f = +1$ fraction is $1.04 \pm 0.19(\text{stat}) \pm 0.06(\text{syst})$ [9]. In the following determination of \mathcal{S} and \mathcal{A} , we fix $\xi_f = +1$. The intermediate meson states are reconstructed from the following decay chains: $\eta' \rightarrow \rho^0(\rightarrow \pi^+ \pi^-) \gamma$ or $\eta' \rightarrow \pi^+ \pi^- \eta(\rightarrow \gamma \gamma)$, $K_S^0 \rightarrow \pi^+ \pi^-$, and $\phi \rightarrow K^+ K^-$.

Candidate $K_S^0 \rightarrow \pi^+ \pi^-$ decays are oppositely charged track pairs that have an invariant mass within 15 (12) MeV/c^2 of the nominal K_S^0 mass for the $B^0 \rightarrow \phi K_S^0$ ($B^0 \rightarrow K^+ K^- K_S^0$) mode. The displacement of the $\pi^+ \pi^-$ vertex from the nominal interaction point (IP) in the plane transverse to the positron beam axis (r - ϕ plane) is required to be greater than 0.1 cm and less than 20 cm. The direction of the combined pion-pair momentum in the r - ϕ plane is required to be within 0.2 radians of the direction defined by the IP and the displaced vertex. We select candidate $\phi \rightarrow K^+ K^-$ decays requiring that the $K^+ K^-$ invariant mass is within 10 MeV/c^2 of the nominal ϕ meson mass, the ϕ meson momentum in the cms exceeds 2.0 GeV/c , and the $K^+ K^-$ vertex is consistent with the IP. Since the ϕ meson selection is effective in reducing background events, we impose only minimal kaon-identification requirements. For selection of non-resonant $K^+ K^- K_S^0$ candidates, more stringent kaon-identification requirements, which retain 86% of K^\pm at a 7% fake rate for π^\pm , are used. In this case, charged tracks that are positively identified as electrons or protons are excluded. In addition to the rejection of ϕ meson candidates, we reject $K^+ K^-$ pairs that are consistent with $D^0 \rightarrow K^+ K^-$ or $\chi_{c0} \rightarrow K^+ K^-$ decay.

For reconstructed $B \rightarrow f_{CP}$ candidates, we identify B meson decays using the energy difference $\Delta E \equiv E_B^{\text{cms}} - E_{\text{beam}}^{\text{cms}}$ and the beam-energy constrained mass $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_B^{\text{cms}})^2}$, where $E_{\text{beam}}^{\text{cms}}$ is the beam energy in the cms, and E_B^{cms} and p_B^{cms} are the cms energy and momentum of the reconstructed B candidate, respectively. The B meson signal region is defined as $5.27 \text{ GeV}/c^2 < M_{\text{bc}} < 5.29 \text{ GeV}/c^2$ and $|\Delta E| < 0.051 \text{ GeV}$ for $B^0 \rightarrow \phi K_S^0$ or $|\Delta E| < 0.040 \text{ GeV}$ for $B^0 \rightarrow K^+ K^- K_S^0$. In order to suppress background from the $e^+ e^- \rightarrow q \bar{q}$ ($q = u, d, s$) and $c \bar{c}$ continuum, we form signal and background likelihood functions, \mathcal{L}_S and \mathcal{L}_{BG} , from a set of variables that characterize the event topology [9, 11]. We determine \mathcal{L}_S from Monte Carlo (MC) and \mathcal{L}_{BG} from data, and impose mode-dependent thresholds on the likelihood ratio $\mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_{\text{BG}})$. The numbers of reconstructed candidates are 59 and 230 for $B^0 \rightarrow \phi K_S^0$ and for $B^0 \rightarrow K^+ K^- K_S^0$, respectively.

For $B^0 \rightarrow \eta' K_S^0$ decay, we use the same selection criteria as those used in our previously published analysis [11] if both of the charged pions in the $\eta' \rightarrow \pi^+ \pi^- \eta$ or the $\eta' \rightarrow \rho^0 \gamma$ decay have associated SVD hits. We also reconstruct events where only one of the charged pions has associated SVD hits. In this case, the requirement on the impact parameter is relaxed for the track without SVD hits, while a higher threshold is imposed on the likelihood ratio. The number of reconstructed $B^0 \rightarrow \eta' K_S^0$ candidates is 311.

Charged leptons, kaons, pions, and Λ baryons that are not associated with the reconstructed f_{CP} decay are used to identify the b -flavor of the accompanying B meson, which decays into f_{tag} . Based on the measured properties of these tracks, two parameters, q and r , are assigned to each event. The first, q , has the discrete value $+1$ (-1) when the tag-side B meson is more likely to be a B^0 (\bar{B}^0). The parameter r is an event-by-event MC-determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for an unambiguous flavor assignment. It is used only to sort data into six intervals of r , according to the estimated flavor purity. The wrong-tag probabilities for each of these intervals,

TABLE I: The numbers of reconstructed $B^0 \rightarrow f_{CP}$ candidates used for \mathcal{S} and \mathcal{A} determination, N_{ev} , and the estimated signal purity in the ΔE - M_{bc} signal region for each f_{CP} mode.

Mode	ξ_f	N_{ev}	Purity
ϕK_S^0	-1	53	$0.67^{+0.07}_{-0.05}$
$K^+ K^- K_S^0$	+1(100%)	191	$0.50^{+0.04}_{-0.03}$
$\eta' K_S^0$	-1	299	0.49 ± 0.05

w_l ($l = 1, 6$), which are used in the final fit, are determined directly from the data. Samples of B^0 decays to exclusively reconstructed self-tagging channels are utilized to obtain w_l using time-dependent B^0 - \bar{B}^0 mixing: $(N_{\text{OF}} - N_{\text{SF}})/(N_{\text{OF}} + N_{\text{SF}}) = (1 - 2w_l) \cos(\Delta m_d \Delta t)$, where N_{OF} and N_{SF} are the numbers of opposite ($B^0 \bar{B}^0 \rightarrow B^0 \bar{B}^0$) and same ($B^0 \bar{B}^0 \rightarrow B^0 B^0, \bar{B}^0 \bar{B}^0$) flavor events. The event fractions and wrong tag fractions for each r interval are described elsewhere [4].

The decay vertices of B^0 mesons are reconstructed using tracks that have enough SVD hits: i.e. both z and r - ϕ hits in at least one SVD layer and at least one additional layer with a z hit, where the r - ϕ plane is perpendicular to the z axis. Each vertex position is required to be consistent with the IP profile, which is determined run-by-run and smeared in the r - ϕ plane by $21 \mu\text{m}$ to account for the B meson decay length. With these requirements, we are able to determine a vertex even with a single track. The vertex position for the f_{CP} decay is reconstructed using charged kaons for $B^0 \rightarrow \phi K_S^0$ and $B^0 \rightarrow K^+ K^- K_S^0$ decays and using charged pions from ρ^0 or η' decays for $B^0 \rightarrow \eta' K_S^0$. The algorithm for the f_{tag} vertex reconstruction is chosen to minimize the effect of long-lived particles, secondary vertices from charmed hadrons and a small fraction of poorly reconstructed tracks [14]. From all the charged tracks with associated SVD hits except those used for f_{CP} , we select tracks with a position error in the z direction of less than $500 \mu\text{m}$, and with an impact parameter with respect to the f_{CP} vertex of less than $500 \mu\text{m}$. Track pairs with opposite charges are removed if they form a K_S^0 candidate with an invariant mass within $\pm 15 \text{ MeV}/c^2$ of the nominal K_S^0 mass. If the reduced χ^2 associated with the f_{tag} vertex exceeds 20, the track making the largest χ^2 contribution is removed and the vertex is refitted. This procedure is repeated until an acceptable reduced χ^2 is obtained.

After flavor tagging and vertex reconstruction, we obtain the numbers of $B^0 \rightarrow f_{CP}$ candidates, N_{ev} , listed in Table I. Figure 1 shows the M_{bc} distributions for the reconstructed B candidates that have ΔE values within the signal region. To assign an event-by-event signal probability for use in the maximum-likelihood fit of the CP -violating parameters, we determine event distribution functions in the ΔE - M_{bc} plane for both signal and background. The signal distribution is modeled with a single two-dimensional Gaussian, where the widths are allowed to float in the fit to data. For the continuum background, we use a linear function for ΔE and the ARGUS parameterization [15] for M_{bc} . We use events outside the signal region as well as a large MC sample to study the background components. The dominant background comes from continuum events. In addition, according to MC simulation, there is a non-negligible ($\sim 8\%$) contamination from $B\bar{B}$ background events in $B^0 \rightarrow \eta' K_S^0$ ($\eta' \rightarrow \rho^0 \gamma$). The contributions from $B\bar{B}$ events are smaller for other decay modes. The contamination of $K^+ K^- K_S^0$ events in the ϕK_S^0 sample (and vice versa) is also small and is treated as a source of systematic uncertainty. Finally, backgrounds from $B^0 \rightarrow f_0(980) K_S^0$ decay, which has the opposite CP eigenvalue to ϕK_S^0 , are found to be

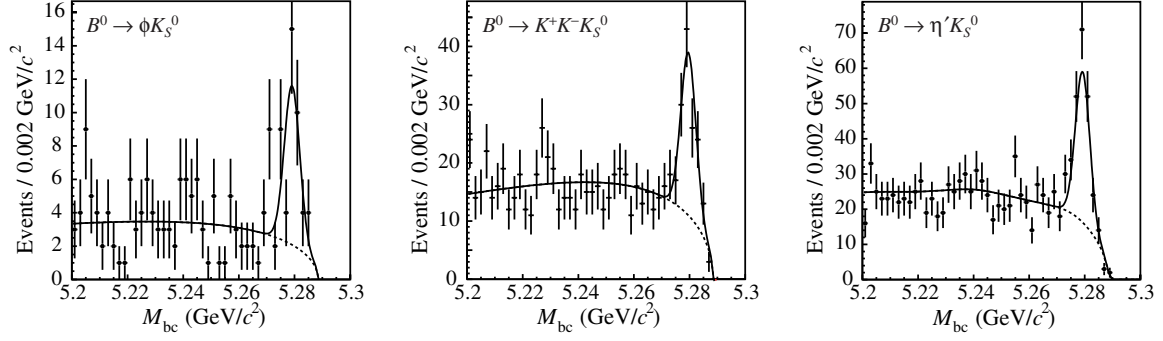


FIG. 1: The beam-energy constrained mass distributions for $B^0 \rightarrow \phi K_S^0$ (left), $B^0 \rightarrow K^+ K^- K_S^0$ (center), and $B^0 \rightarrow \eta' K_S^0$ (right) within the ΔE signal region. Solid curves show the fit to signal plus background distributions, and dotted curves show the background contributions. The background for $B^0 \rightarrow \eta' K_S^0$ decay includes an MC-estimated $B\bar{B}$ background component.

negligible.

We determine \mathcal{S} and \mathcal{A} for each mode by performing an unbinned maximum-likelihood fit to the observed Δt distribution. The probability density function (PDF) expected for the signal distribution is given by Eq. (1) with q replaced by $q(1 - 2w_l)$ to account for the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function $R_{\text{sig}}(\Delta t)$, which takes into account the finite vertex resolution. It is formed by convolving four components: the detector resolutions for z_{CP} and z_{tag} , the shift in the z_{tag} vertex position due to secondary tracks originating from charmed particle decays, and the kinematic approximation that the B mesons are at rest in the cms [14]. A small component of broad outliers in the Δz distribution, caused by mis-reconstruction, is represented by a Gaussian function $P_{\text{ol}}(\Delta t)$. We determine twelve resolution parameters and the neutral- and charged- B lifetimes simultaneously from a fit to the Δt distributions of hadronic B decays and obtain an average Δt resolution of ~ 1.43 ps (rms). We determine the following likelihood value for each event:

$$P_i(\Delta t_i; \mathcal{S}, \mathcal{A}) = (1 - f_{\text{ol}}) \int_{-\infty}^{\infty} \left[f_{\text{sig}} \mathcal{P}_{\text{sig}}(\Delta t', q, w_l) R_{\text{sig}}(\Delta t_i - \Delta t') + (1 - f_{\text{sig}}) \mathcal{P}_{\text{bkg}}(\Delta t') R_{\text{bkg}}(\Delta t_i - \Delta t') \right] d(\Delta t') + f_{\text{ol}} P_{\text{ol}}(\Delta t_i) \quad (3)$$

where f_{ol} is the outlier fraction and f_{sig} is the signal probability calculated as a function of ΔE and M_{bc} . $\mathcal{P}_{\text{bkg}}(\Delta t)$ is a PDF for background events, which dilutes the significance of CP violation in Eq. (1). It is modeled as a sum of exponential and prompt components, and is convolved with a sum of two Gaussians, R_{bkg} , which represents a resolution function for the background. All parameters in $\mathcal{P}_{\text{bkg}}(\Delta t)$ and R_{bkg} are determined by the fit to the Δt distribution of a background-enhanced control sample [16]; i.e. events away from the ΔE - M_{bc} signal region. We fix the τ_{B^0} and Δm_d at their world-average values [17]. The only free parameters in the final fit are \mathcal{S} and \mathcal{A} , which are determined by maximizing the likelihood function

$$L = \prod_i P_i(\Delta t_i; \mathcal{S}, \mathcal{A}) \quad (4)$$

where the product is over all events. Table II summarizes the results of the fit. The table shows the values of \mathcal{A} and $-\xi_f \mathcal{S}$, which, in the SM, is equal to $\sin 2\phi_1$. The first errors are

TABLE II: Results of the fits to the Δt distributions. The first errors are statistical and the second errors are systematic. The third error for the $K^+K^-K_S^0$ mode arise from the uncertainty in the fraction of the CP -odd component.

Mode	$-\xi_f \mathcal{S}$ ($= \sin 2\phi_1$ in the SM)	\mathcal{A} ($= 0$ in the SM)
ϕK_S^0	$-0.73 \pm 0.64 \pm 0.22$	$-0.56 \pm 0.41 \pm 0.16$
$K^+K^-K_S^0$	$+0.49 \pm 0.43 \pm 0.11^{+0.33}_{-0.00}$	$-0.40 \pm 0.33 \pm 0.10^{+0.00}_{-0.26}$
$\eta' K_S^0$	$+0.71 \pm 0.37^{+0.05}_{-0.06}$	$+0.26 \pm 0.22 \pm 0.03$

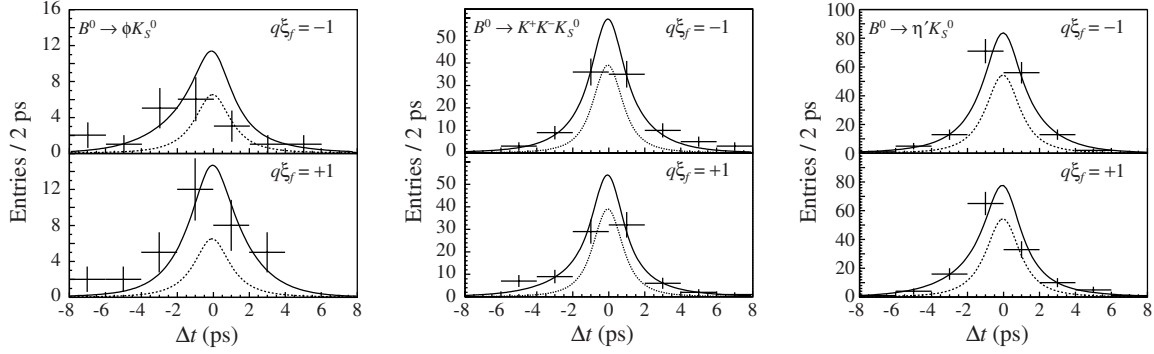


FIG. 2: The Δt distributions for $B^0 \rightarrow \phi K_S^0$ (left), $B^0 \rightarrow K^+K^-K_S^0$ (center), and $B^0 \rightarrow \eta' K_S^0$ (right) decays. The upper and lower plots are for $q\xi_f = -1$ and $q\xi_f = +1$ candidates, respectively. The solid curves show the results of the global fits, and dashed curves show the background distributions.

statistical and the second errors are systematic. The third error for the $K^+K^-K_S^0$ mode arises from the uncertainty in the fraction of the CP -odd component [9]. Figure 2 shows the observed Δt distribution for $q\xi_f = -1$ (upper figure) and $q\xi_f = +1$ (lower figure) event samples for each f_{CP} mode. Figure 3 shows the raw asymmetry in each Δt bin without background subtraction, which is defined by

$$A \equiv \frac{N_{q\xi_f=-1} - N_{q\xi_f=+1}}{N_{q\xi_f=-1} + N_{q\xi_f=+1}}, \quad (5)$$

where $N_{q\xi_f=+1(-1)}$ is the number of observed candidates with $q\xi_f = +1(-1)$. The curves show the results of the unbinned-maximum likelihood fit to the asymmetry distribution, $-\xi_f \mathcal{S} \sin(\Delta m_d \Delta t) - \xi_f \mathcal{A} \cos(\Delta m_d \Delta t)$. These are the first measurements of the CP violation parameters for $B^0 \rightarrow \phi K_S^0$ and $B^0 \rightarrow K^+K^-K_S^0$ decays. The result for $\eta' K_S^0$ supersedes the previous result [11]. We obtain values consistent with the present world average of $\sin 2\phi_1 = +0.734 \pm 0.054$ [18] in $B^0 \rightarrow K^+K^-K_S^0$ and $\eta' K_S^0$ decays, while a 2.1σ deviation is observed in $B^0 \rightarrow \phi K_S^0$ decay.

Fits to the same samples with the direct CP violation parameter \mathcal{A} fixed at zero yield $-\xi_f \mathcal{S} = -0.83 \pm 0.72(\text{stat})$ for $B^0 \rightarrow \phi K_S^0$, $-\xi_f \mathcal{S} = +0.59 \pm 0.47(\text{stat})$ for $B^0 \rightarrow K^+K^-K_S^0$, and $-\xi_f \mathcal{S} = +0.77 \pm 0.38(\text{stat})$ for $B^0 \rightarrow \eta' K_S^0$. As a consistency check for the \mathcal{S} term, we select the charged B meson decays $B^+ \rightarrow \phi K^+$ and $B^+ \rightarrow \eta' K^+$ and apply the same fit procedure. We obtain $\mathcal{S} = 0.05 \pm 0.32(\text{stat})$, $\mathcal{A} = 0.29 \pm 0.24(\text{stat})$ for $B^+ \rightarrow \phi K^+$ decay

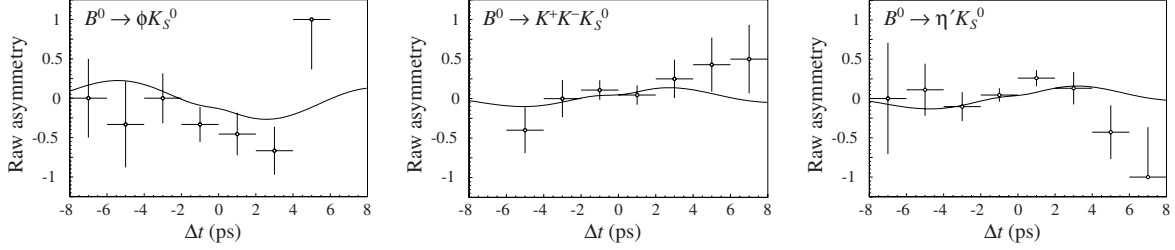


FIG. 3: The Δt asymmetry, A , in each bin for $B^0 \rightarrow \phi K_S^0$ (left), $B^0 \rightarrow K^+K^-K_S^0$ (center), and $B^0 \rightarrow \eta' K_S^0$ (right), respectively. The curves show the results of the unbinned-maximum likelihood fit.

and $\mathcal{S} = -0.03 \pm 0.20(\text{stat})$, $\mathcal{A} = 0.05 \pm 0.13(\text{stat})$ for $B^+ \rightarrow \eta' K^+$ decay. Both results on the \mathcal{S} term are consistent with no CP asymmetry, as expected.

The largest source of systematic error for the $B^0 \rightarrow \phi K_S^0$ mode is the uncertainty in the signal fraction and the background Δt shape (± 0.17 for \mathcal{S} and ± 0.14 for \mathcal{A} in total) determined from the events in the sideband regions in the ΔE - M_{bc} plane. Other significant contributions come from uncertainties in the vertex reconstruction, the resolution function parameters, wrong tag fractions, τ_{B^0} , and Δm_d . We add each contribution in quadrature to obtain the total systematic uncertainty. Systematic uncertainties from these sources are also examined for the other modes. We find that the largest uncertainties arise from the vertex reconstruction (± 0.09 for \mathcal{S} and ± 0.08 for \mathcal{A}) for the $B^0 \rightarrow K^+K^-K_S^0$ mode, and from the resolution function parameters ($^{+0.03}_{-0.04}$ for \mathcal{S}) and the signal fraction (± 0.02 for \mathcal{A}) for the $B^0 \rightarrow \eta' K_S^0$ mode.

In summary, we have performed the first measurement of CP violation parameters in the $B^0 \rightarrow \phi K_S^0$ and $K^+K^-K_S^0$ decays. We also provide an improved measurement for $\eta' K_S^0$ decay. These modes are dominated by the $b \rightarrow s\bar{s}s$ transition and are sensitive to possible new CP -violating phases. Our results for $B^0 \rightarrow \eta' K_S^0$ and $K^+K^-K_S^0$ are consistent with those obtained for $B^0 \rightarrow J/\psi K_S^0$ and other decays governed by the $b \rightarrow c\bar{c}s$ transition. A 2.1σ deviation is observed for $B^0 \rightarrow \phi K_S^0$.

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